In Vitro Performance Testing of Two Arcuate Oscillating Saw Blades Designed for Use During Tibial Plateau Leveling Osteotomy

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Objective: To test the cutting performance of 2 commercially available oscillating saws designed for use during tibial plateau leveling osteotomy (TPLO) and to evaluate the influence of saline irrigation on cutting performance.
Study Design: In vitro experimental study.
Sample Population: Composite polyurethane test blocks (n = 40); 24 mm TPLO saw blades.
Methods: Controlled force cutting tests were performed using custom-made laminated bone substitute blocks to model the canine proximal tibia. Half of the trials were irrigated with 0.9% saline solution. Outcome measures were test block temperature (measured 1.5 mm from the cutting zone), cutting rate, and cutting surface wear. Durability was measured by recording change in performance over multiple consecutive trials.
Results: The Synthes blade cut the test blocks with ~64% less heat generation and at a 63% faster cutting rate compared with the Slocum blade. Although wear of the Synthes blade was ~50% greater after 19 uses, this did not negatively impact cutting performance. Saline irrigation produced no significant effect on peak cutting temperature but significantly reduced cutting rate for both saws.
Conclusions: Our results favor the Synthes blade in terms of cutting performance and the Slocum blade in terms of wear resistance.

Cranial cruciate ligament (CrCL) insufficiency is one of the most common causes of lameness in dogs.[1] Partial or complete CrCL rupture causes stifle joint instability and triggers a cascade of secondary pathologic changes including progressive osteoarthritis and subsequent meniscal injury.[2,3] Numerous surgical techniques have been described to manage CrCL insufficiency, each having potential or proven advantages and disadvantages.[4,5] Tibial plateau leveling osteotomy (TPLO) was first described by Slocum in a patent in 1987 and later in a review article in 1993.[6] The theory behind TPLO is that establishment of dynamic stability to the CrCL deficient stifle negates the requirement for passive restraint against laxity.[6] The surgical procedure itself involves the creation of an arcuate osteotomy in the proximal tibia, rotation of the proximal segment to establish precise manipulation of the tibial plateau slope and stabilization of the proximal segment using a bone plate and screws.[6]

To facilitate the creation of an arcuate osteotomy across the proximal tibia during TPLO, a patent application was submitted in 1989 for a biradial design of oscillating saw blade.[7] The unique feature of this Slocum-designed blade was the property of having inner and outer arcuate surfaces with substantially the same radius of curvature. This feature was said to promote an improved match between the mating surfaces of the osteotomy, thus promoting primary healing after internal fixation of the reduced bone segments. More recently, several other manufacturers have produced oscillating saw blades intended for use during TPLO. However, while these blades are capable of producing an arcuate osteotomy, they do not incorporate the biradial design feature, which remains protected by a US patent at the time of publication.[7]

Despite ubiquitous use of oscillating bone saws in both human and veterinary orthopedic surgery, there have been relatively few studies investigating the influence of surgical blade design on bone cutting performance.[8–13] In studies that have addressed this subject, the outcome measures recorded most frequently were rate of bone removal and

maximum temperature produced by the saw blade.[8–13] The latter is considered an important outcome measure because of the potential for thermal necrosis as a result of the high-speed cutting action of the oscillating saw blade.[14] When generated heat surpasses the threshold temperature of bone tissue, the organic matrix is irreversibly damaged and necrosis of the bony ends may occur.[10] The amount of thermal damage is related to the magnitude of temperature elevation and the time the tissue is subjected to damaging temperatures.[15] Currently, there is some discrepancy as to the exact *in vivo* initiation temperature of cellular damage in bone[12]; however, it is generally agreed that relatively small increases in temperature have an adverse effect on bone. Indeed, Eriksson's microscopic studies of living bone tissue demonstrated that a temperature of as little as 47°C maintained for 1 minute severely impaired bone regeneration in a rabbit model.[16]

Factors reported to influence the performance of oscillating saws during bone cutting experiments include saw blade design,[10–13] durability of the blade,[9,11] application of irrigation fluid,[12–14,17] and feed rate or force applied to the saw.[8–14] We are unaware of any previous studies which have assessed the influence of the above factors on the cutting performance of TPLO oscillating saws. Therefore, we conducted controlled force cutting tests using 2 different TPLO saw blade designs. We investigated the influence of saw blade design and the use of saline irrigation on cutting performance. The durability of 2 different blade designs was also tested. Our outcome measures were temperature elevation, cutting rate, and cutting surface wear (measured using scanning electron microscopy [SEM]).

MATERIALS AND METHODS

Oscillating Saws

The performance of 2 commercially available 24 mm TPLO saw blades manufactured by different companies was compared. The Slocum biradial saw blade (Slocum Enterprises, Eugene, OR) was coupled with the Slocum pneumatic oscillating saw. The saw was powered by regulated, compressed, filtered air at a pressure of 7 bar (100 psi). The oscillating speed at this pressure was measured using a 3D laser vibrometer (Poly Tec CLV 3000, Waldbronn, Germany) as 198 Hz (11880 cycles/min). The Synthes crescenteric saw blade (Synthes, Welwyn Garden, City, UK) was coupled to a Synthes Colibri electric oscillating saw. Using the 12 V rechargeable battery, the oscillating speed was 188 Hz (11,280 cycles/min). To maintain constant power throughout testing, 2 batteries were used, with 1 being charged while the other was in use. The batteries were alternated between trials, with a fresh battery being used for 5 trials without saline irrigation and 5 trials with irrigation. In accordance with the manufacturer's recommendations, both oscillating saw blades were cleaned between trials and the Slocum blade was sharpened between each trial (biradial saw blade sharpener, Slocum Enterprises).

Bone Substitute Preparation (Fig 1)

Composite bone substitute sheets (Sawbones, Malmo, Sweden) were custom manufactured to model the canine proximal tibia, using density values based on previously published data for CrCL-deficient dogs.[18,19] Sample dimensions were predetermined to result in a cut surface area that corresponded to the osteotomy area in a typical clinical situation after TPLO using a 24 mm oscillating saw blade. Data for the area of the osteotomy surface after TPLO were collected from 4 cadaveric specimens (mean cadaveric weight, 23 kg; range, 20–24 kg) used in a previous study.[20]

Digital photographs of the osteotomized surfaces were analyzed using a commercial image-analysis software package (Adobe Photoshop 7, Adobe Systems, London, UK), which demonstrated a mean osteotomy surface area of 546 mm^2. Forty laminated test blocks were produced with identical dimensions (width 59 mm, height 25 mm, depth 21 mm; Fig 1). Each test block consisted of a 15 mm thick 0.32 g/cm^3 closed cell cellular rigid polyurethane foam core, laminated on both sides with 3 mm thick 0.64 g/cm^3 solid rigid polyurethane foam. To simplify subsequent descriptions, the laminated sheets on the leading and trailing surfaces of the test block are denoted cis-cortex and trans-cortex, respectively. The width of the saw blade exceeded the test block height by 10.5 (Synthes) to 17 mm (Slocum), allowing the kerf of the saw blade to exit the sample on either side during testing (Fig 2). This allowed simulation of the clinical scenario while maintaining a repeatable cut surface area approximating 546 mm^2.

A series of three 6 mm deep, 1 mm diameter holes were drilled at distances of 1 mm (cis-cortex), 10 mm

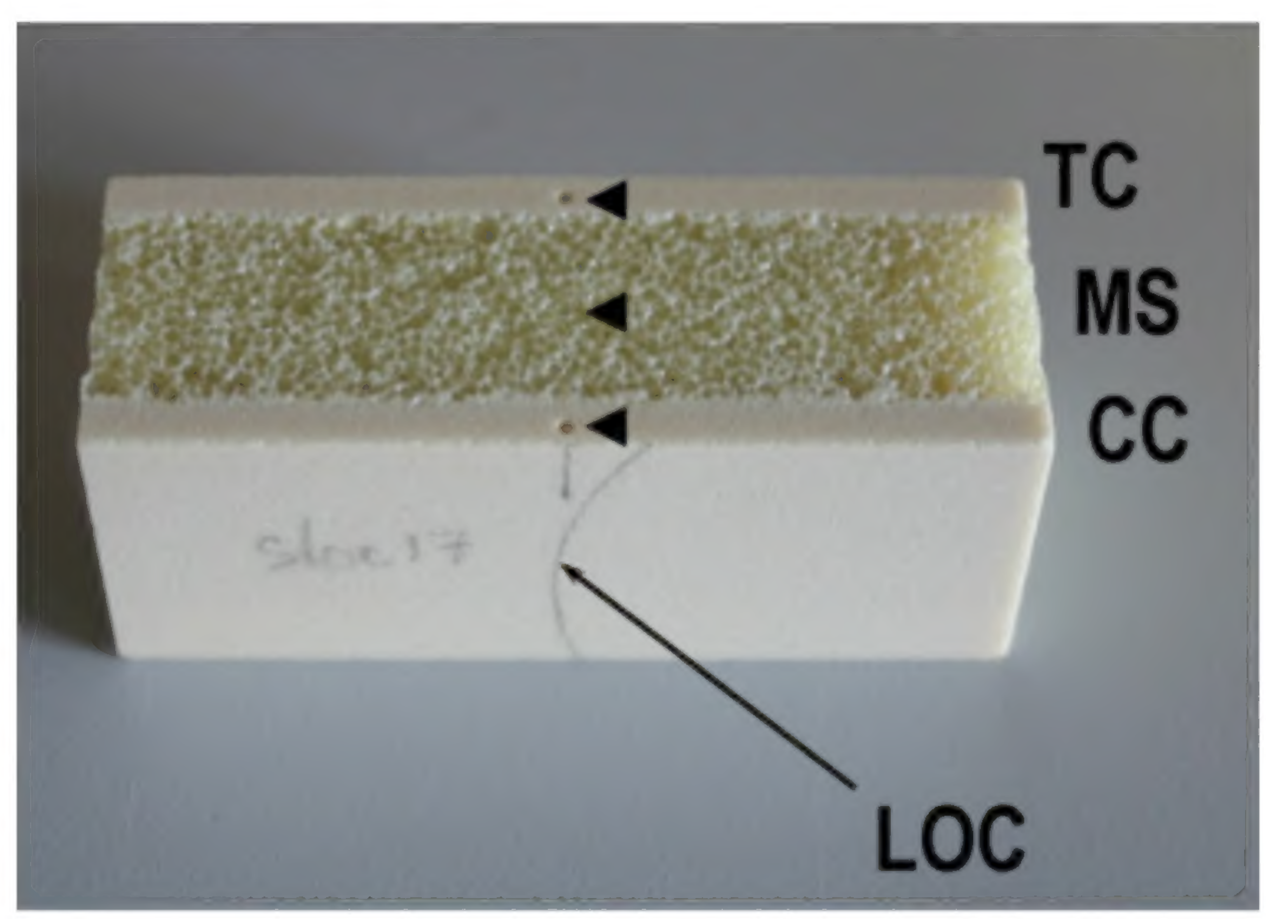

Figure 1 Test block sample photographed from the leading edge. Each block comprised a 15 mm thick polyurethane foam core, laminated on either side with 3 mm thick solid polyurethane foam "cortices." The test block dimensions produced a cut surface area which modeled TPLO using a 24 mm radius blade on a 20–24 kg dog.[20] The density values of the composite sample were equivalent to those of the proximal tibia of a dog affected by CrCL disease.[18,19,23] LOC, line of cut; CC, cis-cortex; MS, mid-substance; TC, trans-cortex. Arrowheads show the 3 thermocouple holes drilled in series to a depth of 6 mm.

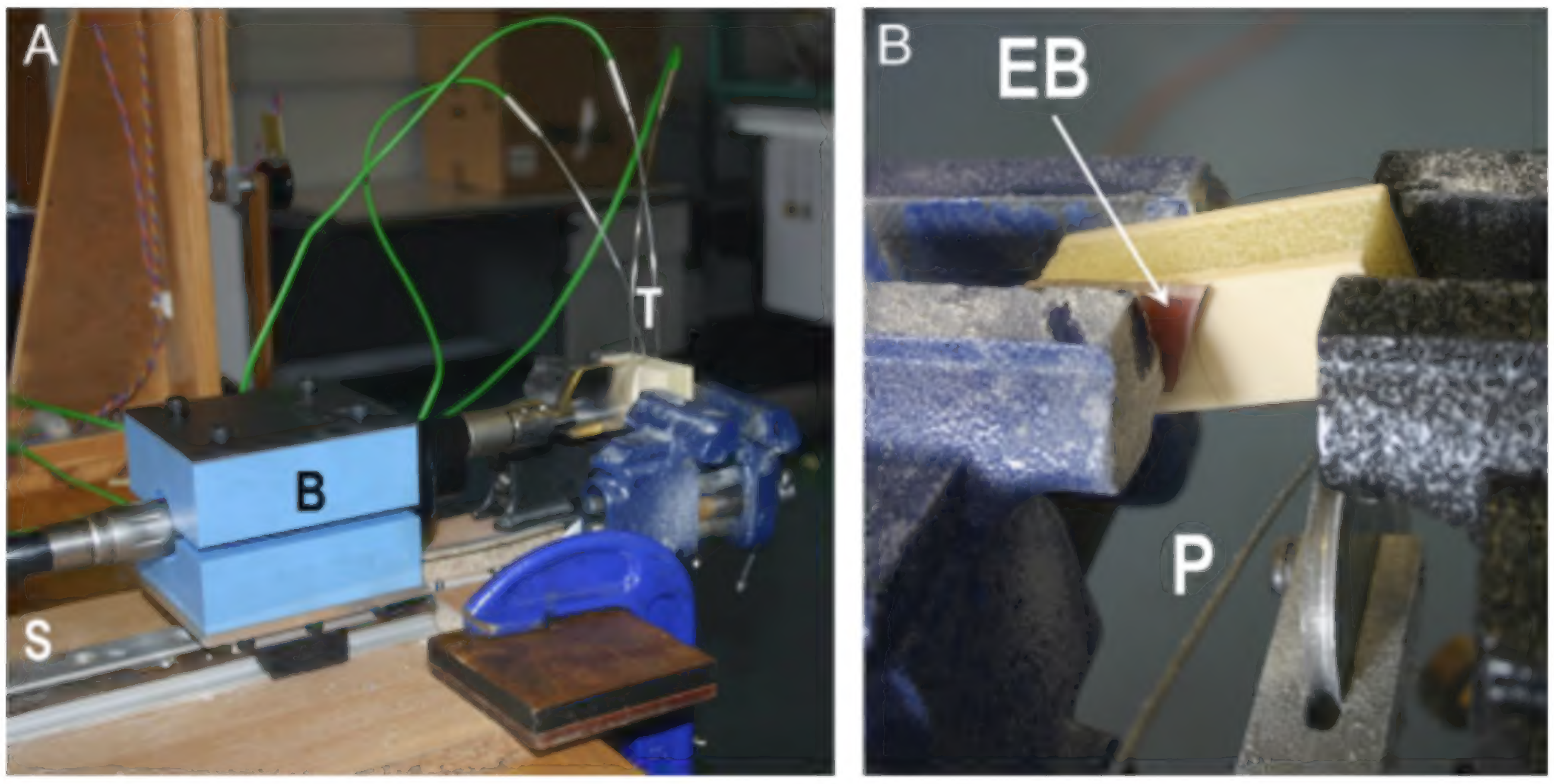

Figure 2 Experimental rig. (A) Thermocouples (T) were mounted in series to a depth of 6 mm within the test block, so that temperature was recorded within 1.5 mm of the cutting zone. Each oscillating saw was mounted in an injection-molded brace (B) attached to a low-friction slider (S). A pulley, cable and weights attached to the leading edge of the brace provided a fixed static force during cutting experiments. (B) Test blocks were mounted between paired base clamps and an epoxy bumper (EB) was used to prevent skipping of the saw causing accidental trauma to the thermocouples. The pulley (P) was mounted to the horizontal base plate immediately subjacent to the test block mounting.

(mid-substance) and 20 mm (trans-cortex) from the leading surface of the test block. A pencil mark corresponding to the position of the thermocouples was drawn on the leading surface (Fig 1). A plastic template of the oscillating saw blades was used to allow the intended line of cut to be marked at a distance of 1.5 mm from the tip of the thermocouple holes.

Experimental Rig (Fig 2)

Test blocks were clamped onto a horizontal base plate using paired bench clamps (Wilton Tool Group, Elgin, IL). The saw assembly consisted of the oscillating saw, mounted in an injection-molded brace, attached to a low-friction custom-built slider, which was free to travel along the guide. To provide a fixed static force during cutting experiments, a system of a pulley, cable and weights was connected to one side of the slider. The saw assembly was positioned with the blade contacting the leading edge of the test block, allowing the block to be adjusted to align the blade precisely with the intended cut mark. A 3-mm-thick epoxy "bumper" was positioned immediately adjacent to the blade to prevent skipping of the saw resulting in accidental trauma to the thermocouples during testing. After verification of correct alignment, the saw assembly was repositioned with the blade 2 mm clear of the leading edge of the sample. The powered saw was then activated, gently lowered onto the test block, and allowed to cut the sample using a designated predetermined force of 5 N. Each trial was timed from the point of first contact of the blade with the test block to cut completion using a commercial stopwatch (Fastime, Pyramid Technologies, Meriden, CT). A total of 20 trials were performed using one of each blade design. This number was chosen due the current manufacturer's recommendation for a maximum of 20 uses before disposing of the Synthes blade.

Temperature Measurement

Temperature measurements were made through three 1 mm diameter mineral-coated Type K–310 stainless-steel thermocouples (TC Direct, Uxbridge, UK), mated with a computer workstation. The computer interface measured temperature input from the probes versus time, with a sampling frequency of 50 Hz. A total sampling duration of 40 seconds was established based on preliminary testing using a new Synthes blade and a force of 5 N. Maximum operating temperature was 1100°C, and instrument error was $\sim\pm 1.0$°C. The assembled temperature recording device was calibrated with water at 14°C, 29°C, and 80°C. Signals from the thermocouples were linear throughout the temperature range of interest. Before testing, the thermocouples were press-fit into the predrilled holes in the testing blocks and labeled as thermocouples 1 (cis-cortex), 2 (mid-substance), and 3 (trans-cortex). Ambient temperature was monitored throughout using a separate K-type thermocouple interfaced with a digital thermometer (Maplin Electronics, Rotherham, UK).

Irrigation

Saline irrigation was delivered to the junction of the oscillating saw blade and leading edge of the test block. A pressure infuser bag (Infu-Surg, Ethox, Buffalo, NY) was used to apply a constant pressure of 165 mmHg to a 1 L bag of room temperature (28°C) 0.9% NaCl solution. This produced a precalculated fluid flow rate of ~80 mL/min. The junctions of the thermocouples with the test block were protected from direct exposure to the irrigation fluid by application of a plug of moldable synthetic rubber polymer (BluTak, Bostik, UK; Fig 3). A sample of the polyurethane cutting debris (Fig 3) was collected at the conclusion of the final irrigated cutting trial. This sample was examined using oil immersion light microscopy at $\times$ 125 magnification.

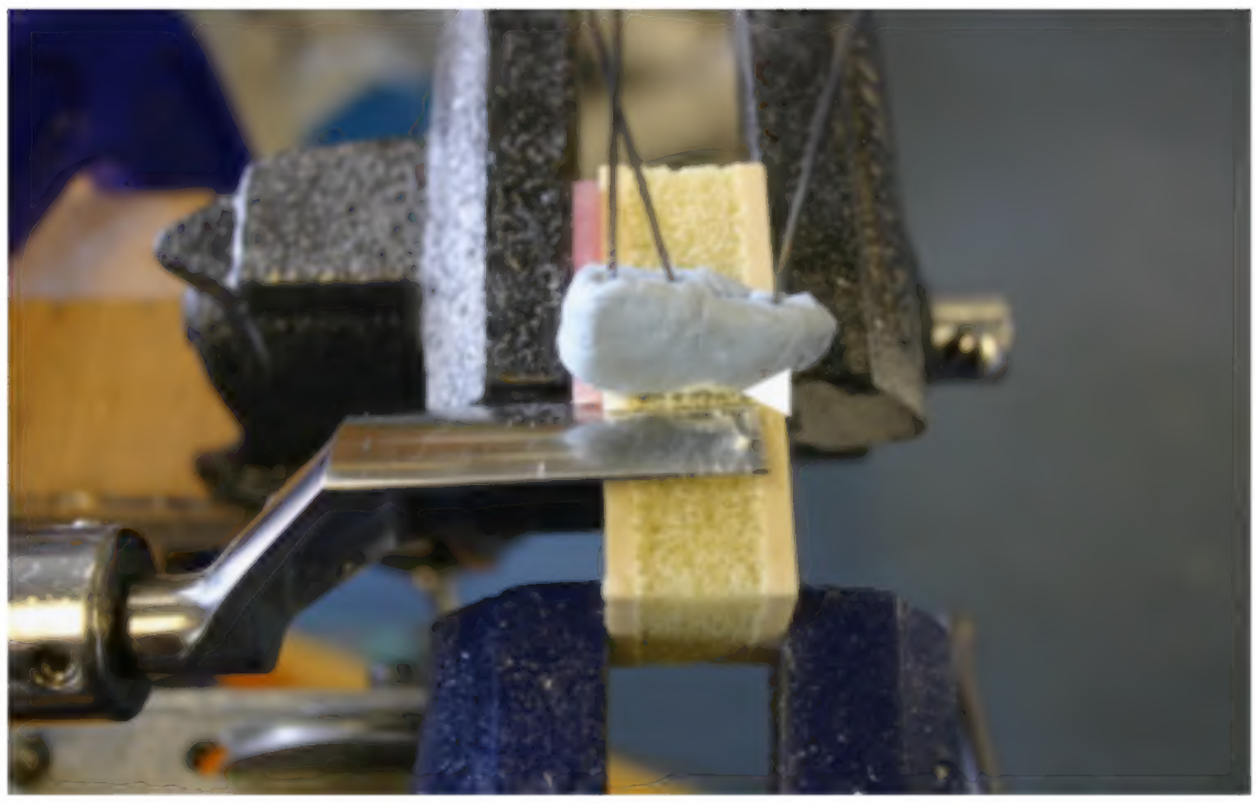

Figure 3 Skyline photograph of an irrigated trial using the Slocum Enterprises blade. The debris produced during the irrigated trials formed a chalky precipitate on the surfaces of the blade and rubber polymer plug (arrowhead).

Debris size and morphology was compared with that of debris produced during TPLO of cadaveric canine bone, using data collected in a previous study.[20]

Experimental Necrosis Limit

Based on a previous study,[12] a temperature of 50°C was established as a necrosis limit for investigational purposes. This temperature limit is dependent upon the fact that the bone cell *in vivo* is initially at 38°C, so that a temperature rise >12°C (50°–38° = 12°) is sufficient to initiate thermal cellular damage. Measurements reported in this study are expressed as elevations from baseline, because of the fact that test blocks were maintained at room temperature rather than 38°C during the experimental procedure.

Saw Blade Durability

The cutting surfaces of both saw blades were examined using an environmental SEM (Quanta 200F, FEI Company, Hillsboro, OR) at ×27–500 magnification. Differences in saw blade anatomy were recorded including tooth height, width, pitch, inclination angle, and offset. The cutting edges were photographed in 2 planes, with one plane perpendicular and the other plane parallel to the cutting surface. Metallurgic investigation was performed via energy-dispersive analysis by X-ray of the 2 blades (EDX, FEI Company). Surface wear was recorded as loss in tooth height and area after 20 consecutive uses, with only the central tooth and adjacent valleys being used for this comparison.

Test Block Trial Reduction

Trial reductions of the test blocks were performed upon completion of the cutting tests, to permit subjective visual analysis of reduction quality.

Statistical Analysis

Cutting Temperature. Scientific hypotheses are stated as follows, and are divided into 4 parts: (1) temperatures measured within the test blocks will increase above the necrosis limit of 12°C (above baseline) during testing with either saw blade design; (2) no significant difference will be found in peak temperature measurements or time duration above the necrosis limit between the 2 different saw blade designs; (3) use of saline irrigation will significantly decrease peak temperatures and durations above the necrosis limit compared to tests performed without irrigation; and (4) Peak temperature measurements will increase as a result of multiple tests using a single blade, because of wear of the cutting surface.

Cutting Rate. Cutting rate was determined by dividing the total depth of the test block (21 mm) by the time taken to complete the cut, and is expressed in units of mm/s. Scientific hypotheses are divided into 3 parts: (1) there will be no statistically significant difference in cutting rate between the 2 different blade designs; (2) cutting rate will not be affected by the use of saline irrigation; and (3) cutting rate will decrease as a result of multiple tests using a single blade, because of wear of the cutting surface.

Saw Blade Durability. It was hypothesized that a statistically significant difference in durability would exist between the 2 saw blade designs, with the Synthes blade being less durable over a total of 20 uses.

Initial exploratory data analysis was undertaken. General linear models were fitted to address the above hypotheses. The first model used log peak cutting temperature as the outcome and included saw type, thermocouple position, irrigation, and trial number as potential explanatory variables. The second model included the same explanatory variables with time above necrosis limit as the outcome variable and the third model used cut rate as the outcome, and considered the explanatory variables as described, with the exception of thermocouple. All plausible interactions were considered and the models were fitted using a backwards-stepwise algorithm, considering P values and maximizing the adjusted R^2. Post hoc pairwise comparisons were undertaken, where possible, adjusting for multiple comparisons using a Bonferroni correction. Significance was set at $P < .05$. All analyses were performed using SPSS software (IBM, Chicago, IL).

RESULTS

Saw Blade Anatomy (Table 1, Fig 4)

Both oscillating saw blades are arcuate with a 24 mm radius of curvature. They comprise a cutting edge, blade, and mounting hub. The Synthes mounting hub consists of a stainless-steel (ISO 1.4310) snap-ring and star-drive countersink screw, which is compatible with the TPLO saw attachment on the Colibri battery-driven power tool. The Slocum mounting hub is triangular and is compatible with either a pneumatic or electric Slocum oscillating saw, via an interference screw coupling system. The blade thickness of

Table 1 Saw Blade Anatomy

	Synthes	Slocum
Design	Crescenteric	Biradial
Stainless-steel grade	ISO 1.4034	N/A
Blade length (mm)	68	77
Blade width (mm)	35.6	42
Thickness (mm)	0.6	1.2 mm (center), 0.6 mm (edge)
Tooth offset (mm)	Plus 0.05 each side	None
Pitch (teeth/mm)	1	0.67
Tooth height (mm)	0.79	1.15
Tooth wedge angle	40°	50°
Tip width (μm)	8.75	43*
Oscillating arc displacement	4.4°	N/A
Oscillating speed (cycles/min)	11,280	11,880

*Tip width measured at the mid-point of the central tooth.
N/A Not Available.

the Synthes saw is uniform at 0.6 mm, while the biradial design of the Slocum saw produces a maximum thickness of 1.2 mm, tapering to 0.6 mm at either edge.

The cutting teeth are described by pitch, offset, and symmetry. The pitch is the number of teeth per unit width of the blade, and is 33% greater (1 versus 0.67 teeth/mm) for the Synthes saw compared with the Slocum saw. Tooth offset describes lateral deviation of the cutting teeth, such that each successive tooth is alternated to opposing sides of the blade. The Synthes blade has 0.05 mm tooth offset in either direction, resulting in a cutting thickness of 0.7 mm, while the Slocum blade has zero tooth offset (i.e. the blade thickness is the same at the level of the cutting surface and blade). Both blades have symmetric tooth geometry about the axis parallel to the cutting direction. The Synthes cutting teeth are separated by valleys occupying a total of 40% of the cutting surface, while the teeth of the Slocum blade are separated by a continuous concave valley with a radius of curvature of 200 μm.

The shape of the tooth is defined by the tooth height and wedge angle. The Slocum tooth is 45% taller than the Synthes tooth (1.15 versus 0.79 mm) and the wedge angle is 10° larger (50° versus 40°). For both saw designs, the tip of the tooth trails its base during cutting procedures, allowing the teeth to cut during the left and right motion of the oscillating blade. The cutting edge of the tooth is termed the rake face and the angle formed between the rake face and a line drawn perpendicular to the cutting direction is the rake (landing) angle. This angle is negative for both saw designs and measures $-20°$ and $-25°$ for the Synthes and Slocum blades, respectively.

The Synthes blade is fabricated from ISO 1.4034 stainless steel (International Organization for Standardization). Data for the grade of stainless steel was not released by Slocum Enterprises; however, EDX analysis revealed a similar profile, consistent with martensitic stainless steel of an equivalent grade to the Synthes blade.

Cutting Temperature (Figs 5 and 6; Table 2)

Readings from the first 2 trials with either saw blade were excluded from data analysis as a result of accidental thermocouple damage (Synthes) and a computer workstation recording error (Slocum). This resulted in a total number of complete trials of 18 for each blade, with 9 trials in each group being performed with saline irrigation.

The predetermined necrosis limit of 12°C above baseline was exceeded at the mid-substance thermocouple in 16/18 trials without the addition of saline irrigation.

Significant differences in peak temperature ($P < .001$) and time above necrosis limit ($P < .001$) were found between saws. The Synthes saw was found to have a mean peak temperature that was, on average, 13.5°C lower, and a time above the limit of necrosis that was, on average, 5.9 seconds less than the Slocum saw. Similarly, differences were found to exist between thermocouples for both peak temperature ($P < .001$) and time above necrosis ($P < .001$). Regardless of saw design, the mid-substance thermocouple was significantly hotter for a longer duration than either the cis- or trans-cortex thermocouples (Table 2).

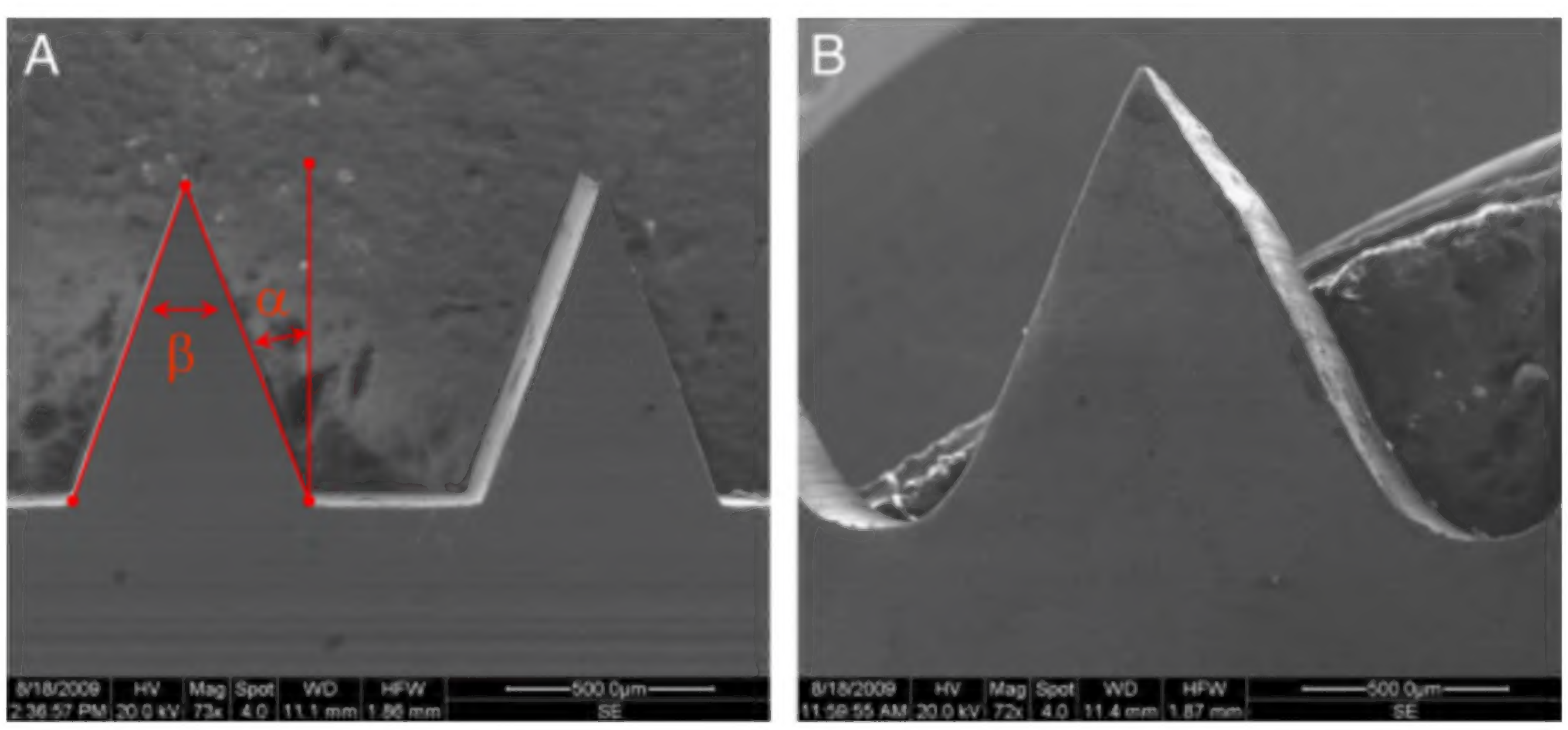

Figure 4 Saw tooth anatomy (SEM – scale bar 500 μm). (A) Unused Synthes saw tooth. α = rake angle, β = wedge angle. (B) Unused Slocum saw tooth. Note the larger tooth dimensions and continuous concave valley separating each tooth.

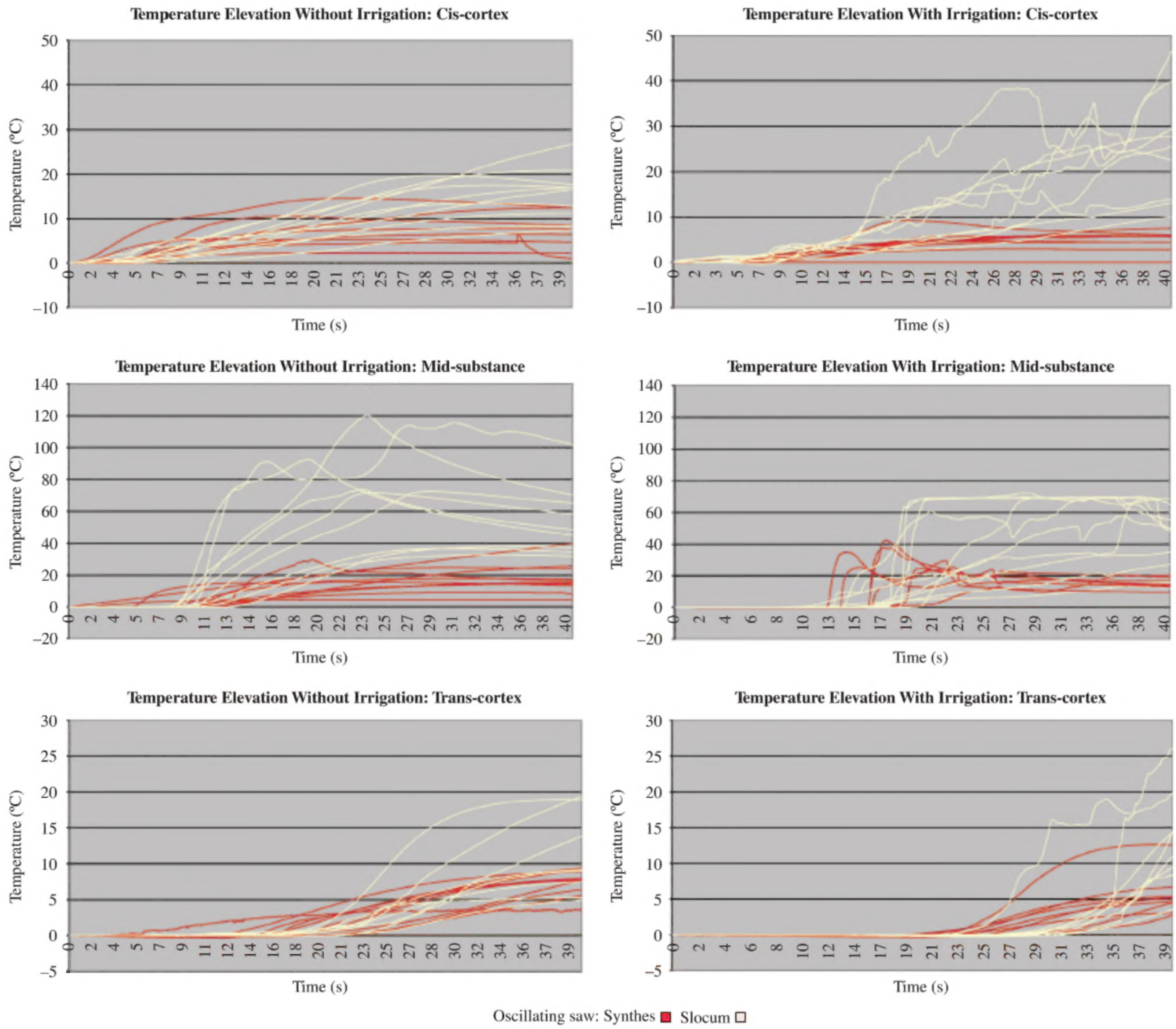

Figure 5 Real-time temperature curves for thermocouples 1 (top – cis-cortex), 2 (middle – mid-section) and 3 (bottom – trans-cortex). For each thermocouple, peak temperatures were recorded when the cutting zone was in close proximity. Note the *x*-axis scales vary between thermocouples 1, 2, and 3, with the highest peak temperatures (up to 120°C above baseline) recorded within the mid-substance of the test block (thermocouple 2).

Effect of Saline Irrigation on Cutting Temperature (Table 2)

The 12°C necrosis limit was exceeded at the mid-substance thermocouple in all 18 trials that incorporated saline irrigation. There was no significant independent effect of irrigation on peak temperature or time above the necrosis limit, even after controlling for blade design and thermocouple location. Multivariate analysis revealed complex 3-way interactions between saw design, use of irrigation, and thermocouple position ($P = .004$). The clinically relevant interaction was reduction in mean temperature at the cis-cortex thermocouple when irrigation was applied to the Synthes blade (temperature elevation for the Slocum saw). The opposite interaction occurred at the mid-substance thermocouple (i.e. temperature elevation with irrigation applied to the Synthes blade and temperature reduction with irrigation applied to the Slocum blade). The polyurethane cutting debris had a crystalline morphology (Fig 7). The diameter range of 5–25 μm was comparable to that of bone debris collected in a previous laboratory-based TPLO experiment.[20]

Cutting Rate (Fig 8)

The presence of an initial outlier value (Synthes saw) is of questionable relevance (see "Discussion"). The data were

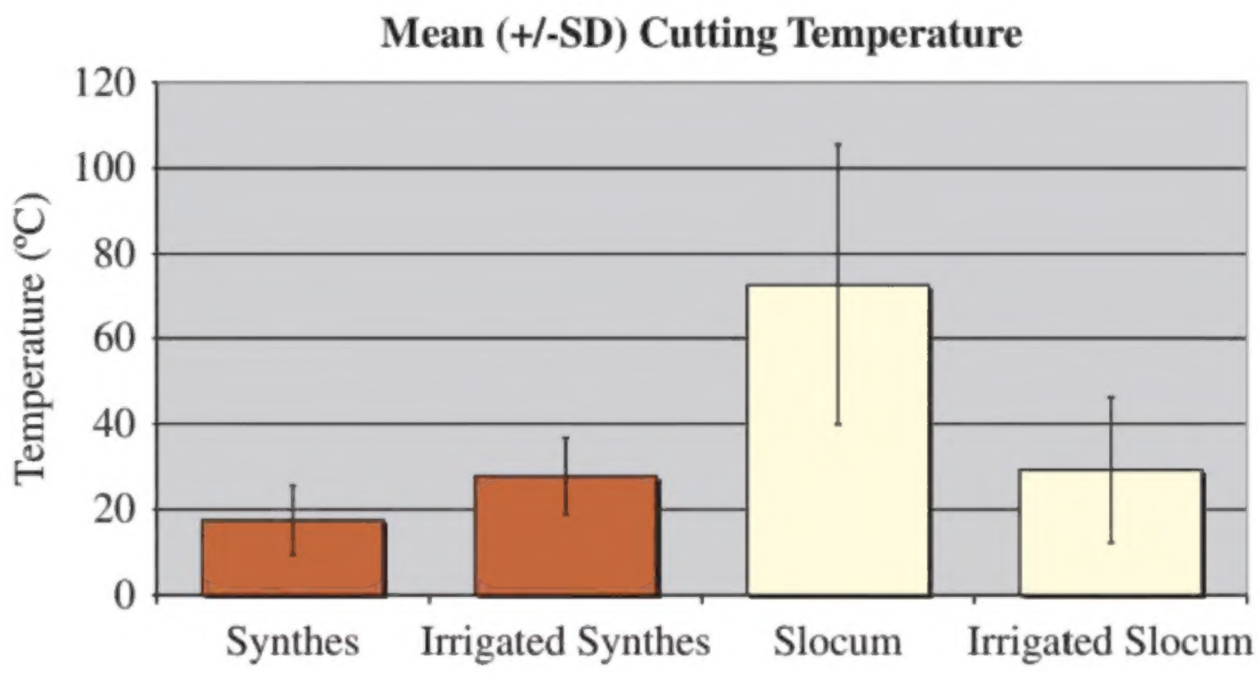

Figure 6 Mean peak cutting temperatures (°C above baseline) over 20 trials. The Synthes blade cut at a significantly lower temperature ($P < .001$) than the Slocum blade and use of saline irrigation did not exert a significant cooling effect on either blade.

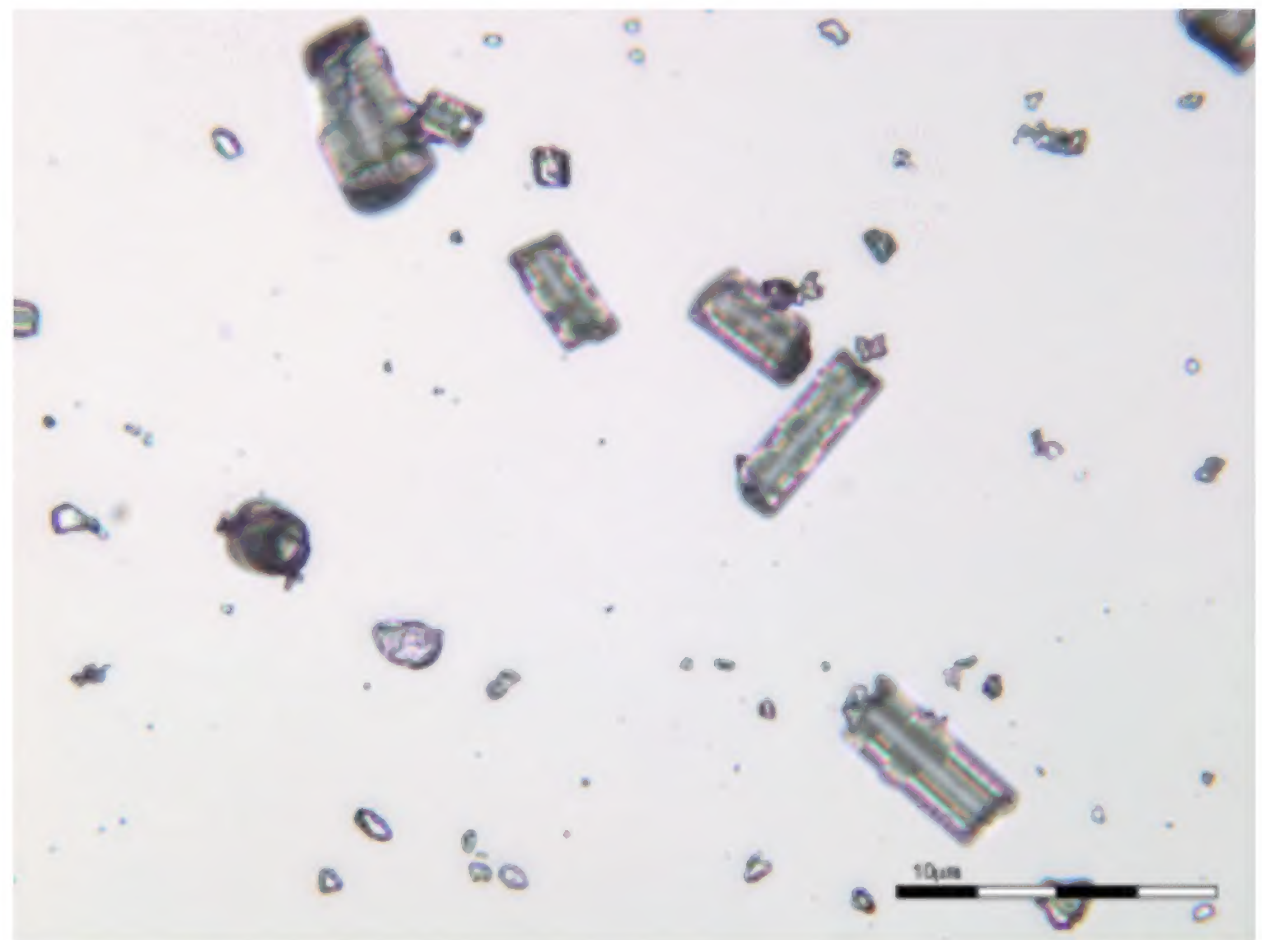

Figure 7 Photomicrograph of cutting debris in solution. May-Grunwald-Giemsa (scale bar 10 µm). Note the crystalline morphology of the debris. The diameter range of 5–25 µm was comparable to that of bone debris collected in a previous laboratory-based TPLO experiment.[20]

analyzed with exclusion of the outlier. Effects of saw design and irrigation were both significant for cut rate ($P < .001$). It was found that the Synthes saw cut with a mean rate that was 0.229 mm/s faster than the Slocum saw. Irrigation was associated with a mean 0.317 mm/s reduction in cut rate ($P < .001$).

Durability (Figs 9 and 10; Table 3)

Wear expressed in terms of loss in tooth height was 32.4% and 10.6% for the Synthes and Slocum blades, respectively. Increasing trial number was not associated with elevation in temperature or reduction in cut rate and was not included in the final model.

Test Block Trial Reduction (Fig 11)

Visible gaps were consistently noted at the peripheral margins of the mated surfaces. There was no subjective difference in reduction quality for test blocks cut with the Synthes blade compared with the Slocum blade.

DISCUSSION

A prerequisite for performing TPLO as described by Slocum is the ability to create an arcuate osteotomy across the proximal tibia using an oscillating bone saw. Although a potential benefit of Slocum's biradial design on osteotomy reduction has been proposed,[7] no clinical advantage to the selective use of this design has been proven. In addition, the clinical implication of variations in cutting surface geometry for different TPLO saws has not been previously investigated. We examined the influence of saw blade design and the use of saline irrigation on the cutting performance of 2 commercially available TPLO saw blades using a controlled laboratory test method. We found that although the working principle was similar between both blades, the performance characteristics, including cutting rate and temperature, were significantly different. Our results show that the Synthes blade cut the test blocks with ~64% less heat generation and at a 63% faster cutting rate compared with the Slocum blade. Time spent above the 12°C necrosis limit was 45% shorter for the Synthes blade, and neither

Table 2 Test Block Temperature Change Measured 1.5 mm from the Cutting Zone, Expressed as Elevations Above Baseline (Room) Temperature

		Mean Peak T (°C) [Time Above Necrosis Limit (s)]	
	Thermocouple	Without Irrigation	With Irrigation
Synthes	Cis-cortex	9.3 [5.2]	5.2 [0]
	Mid-substance	17.5 [17.6]	27.8 [19.1]
	Trans-cortex	7.5 [0]	6.3 [0.6]
Slocum	Cis-cortex	15.7 [11.6]	25.8 [13.1]
	Mid-substance	72.7 [27.6]	59.9 [20.7]
	Trans-cortex	10.5 [2.8]	17.6 [2.1]

Time spent above the 12°C necrosis limit is shown in parentheses. Total sampling time for each trial was 40 seconds.

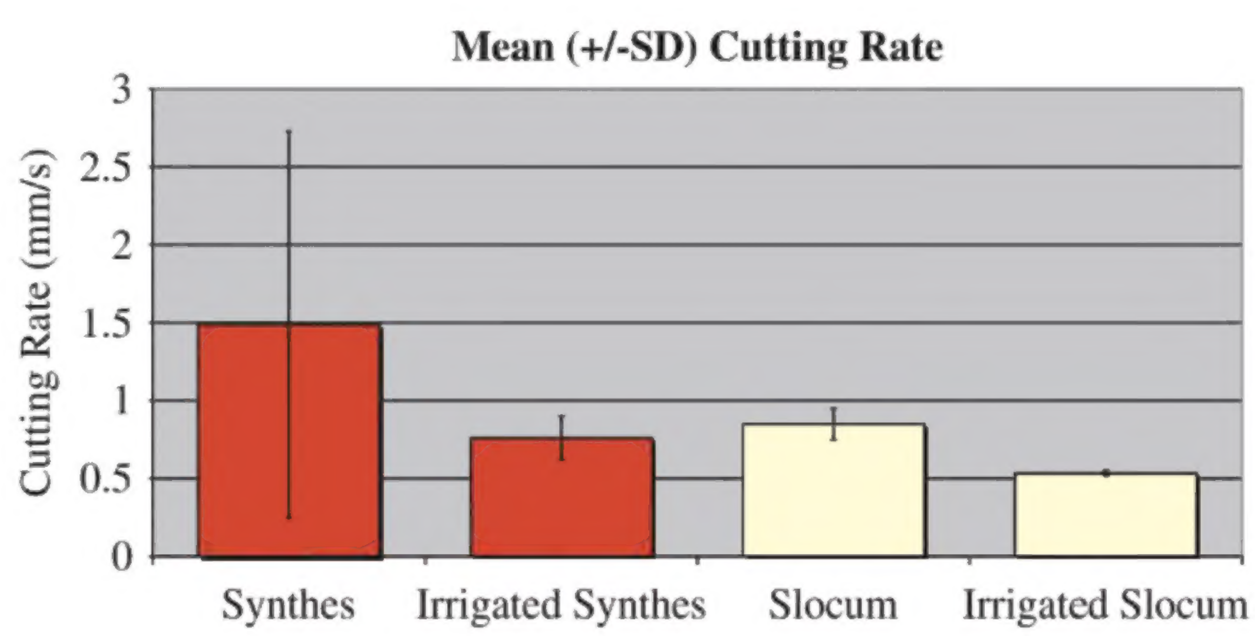

Figure 8 Mean cutting rate (mm/s) over 20 trials. The Synthes blade cut at a significantly faster rate than the Slocum blade ($P < .001$) and saline irrigation was associated with a significant reduction in cutting rate ($P < .001$). The wide SD for the nonirrigated Synthes blade is accounted for by the outlying data point for the first trial, which was over 3 times faster than all subsequent trials.

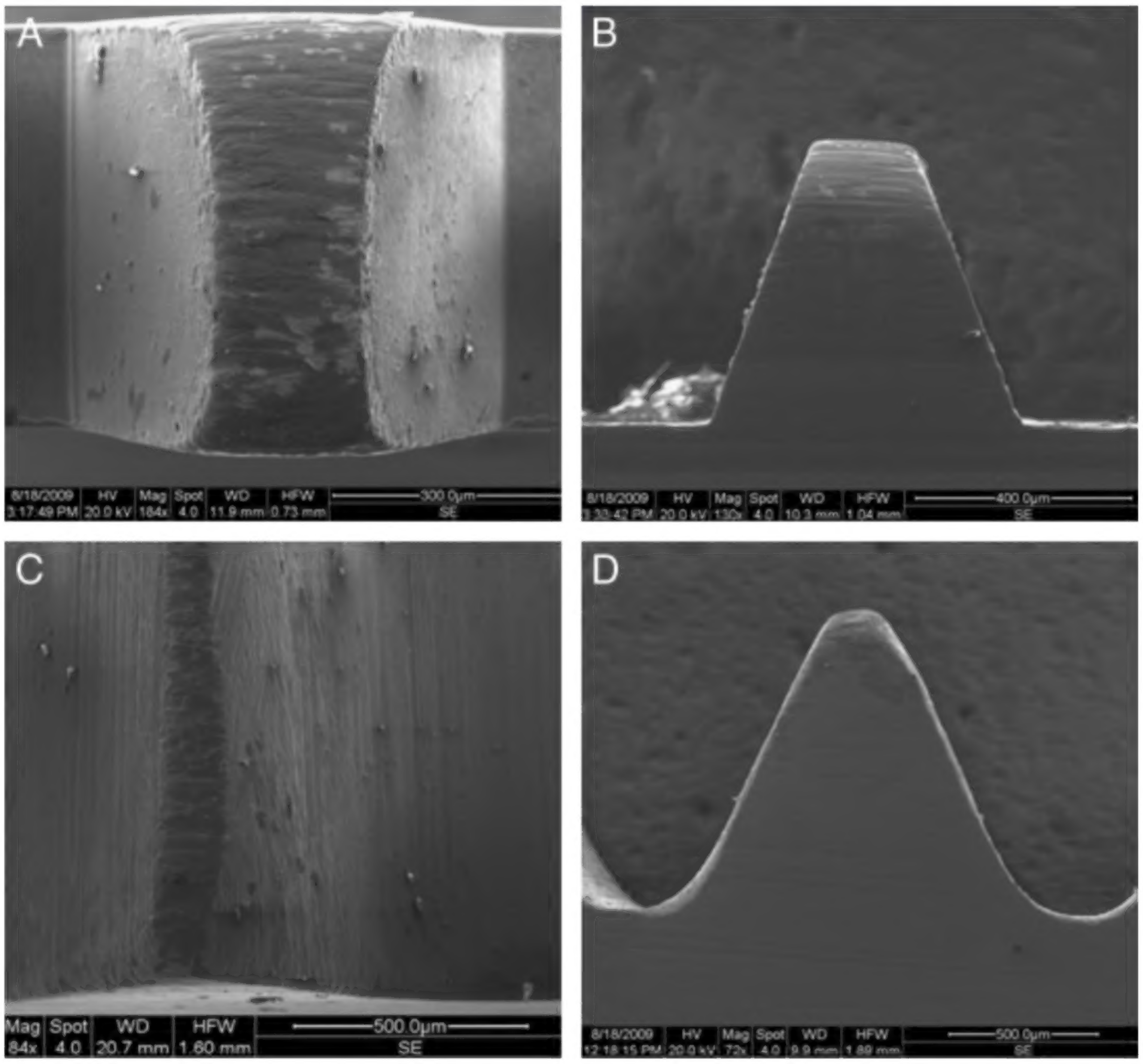

Figure 9 SEM photomicrographs of the cutting teeth after 20 trials (scale bar 300–500 μm). (A) Synthes tooth imaged perpendicular to the cutting surface. Striations can be seen in a plane parallel to the cutting direction. The width of the tip increased from 8.75 (new blade) to 195 μm (20 uses). (B) Synthes tooth imaged parallel to the cutting surface. A 32% reduction in tooth height occurred over 20 uses. (C) Slocum tooth imaged perpendicular to the cutting surface. The width of the tip measured at the center of the tooth increased from 43 (new blade) to 195 μm (20 uses). (D) Slocum tooth imaged parallel to the cutting surface. A 10.6% reduction in tooth height occurred over 20 uses.

peak temperature nor time spent above the necrosis limit was influenced by the application of saline irrigation, regardless of blade design. Wear of the Synthes blade was ~50% greater after 19 trials. However, this difference did not impact negatively on cutting performance, with both blades retaining good durability throughout testing.

Criteria used to support the use of a particular oscillating saw blade include cutting performance, durability, cost, and ease of use.[10] Quantifying oscillating saw performance in terms of the magnitude and duration of temperature elevation within the bone being cut has been advocated because thermal damage to the cut bone surface could compromise its regenerative capacity or predispose it to infection.[12,16,17] Previous laboratory-based experiments and clinical trials have demonstrated temperature elevations far exceeding the predetermined thermal necrosis limit of 45–50°C.[8,12,13,17,21] One clinical trial during human knee joint replacement indicated saw temperatures exceeding 200°C when irrigation was not used.[12] Factors reported to influence this temperature elevation include features intrinsic to the oscillating saw itself, including cutting surface geometry,[10–13] oscillation velocity, feed rate,[8–14] and durability[9,11]; and extrinsic factors including the application of irrigation fluid,[12–14,17] and the physical characteristics of the substance being cut.

Physical Characteristics of the Bone Substitute

The primary limitation of *in vivo* studies which test cutting performance is related to the challenge of measuring temperature change within the bone being cut.[22] Most laboratory-based studies investigating the performance of orthopedic cutting tools substitute cadaveric bone trials for *in vivo* testing, most commonly using bone of bovine origin.[8–13,17] To appropriately model the *in vivo* cutting scenario, selection of a substitute with an appropriate density is critical. We performed preliminary tests to compare temperature elevations within canine cadaveric proximal tibias and Sawbone test block samples with variable densities and thermal conductivities. It was established that cutting tests using polyurethane foam cancellous test blocks of an appropriate density yielded cutting rates and temperatures similar to those seen in tests on cadaveric canine tibias. In contrast, tests using cortical Sawbone test blocks

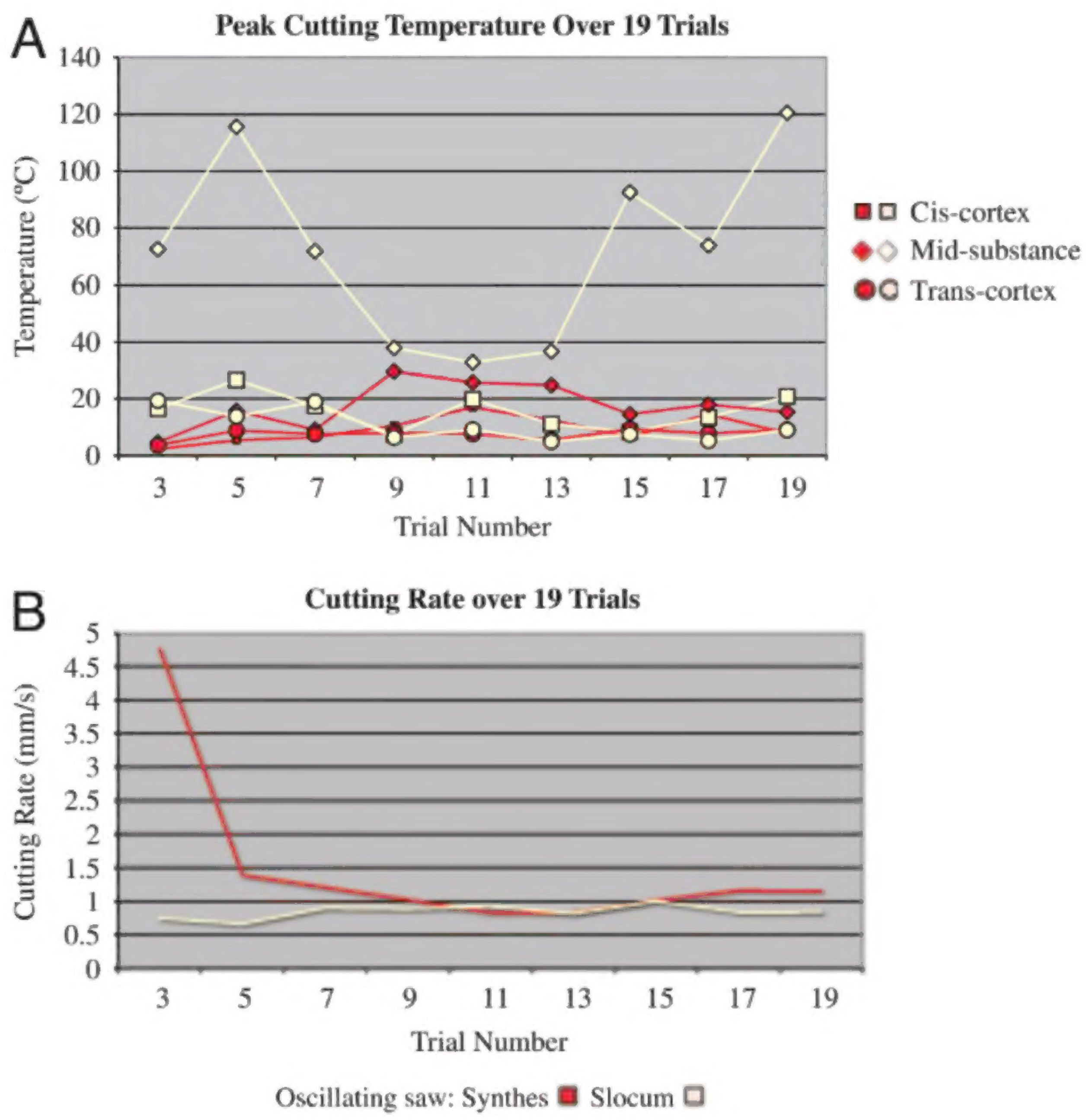

Figure 10 Durability measured as (A) change in peak cutting temperature, and (B) change in cutting rate over 19 trials. Neither peak temperature nor cutting rate were significantly altered by repeated use. Data presented are for nonirrigated trials only (19 trials are presented as the 20th trial was irrigated).

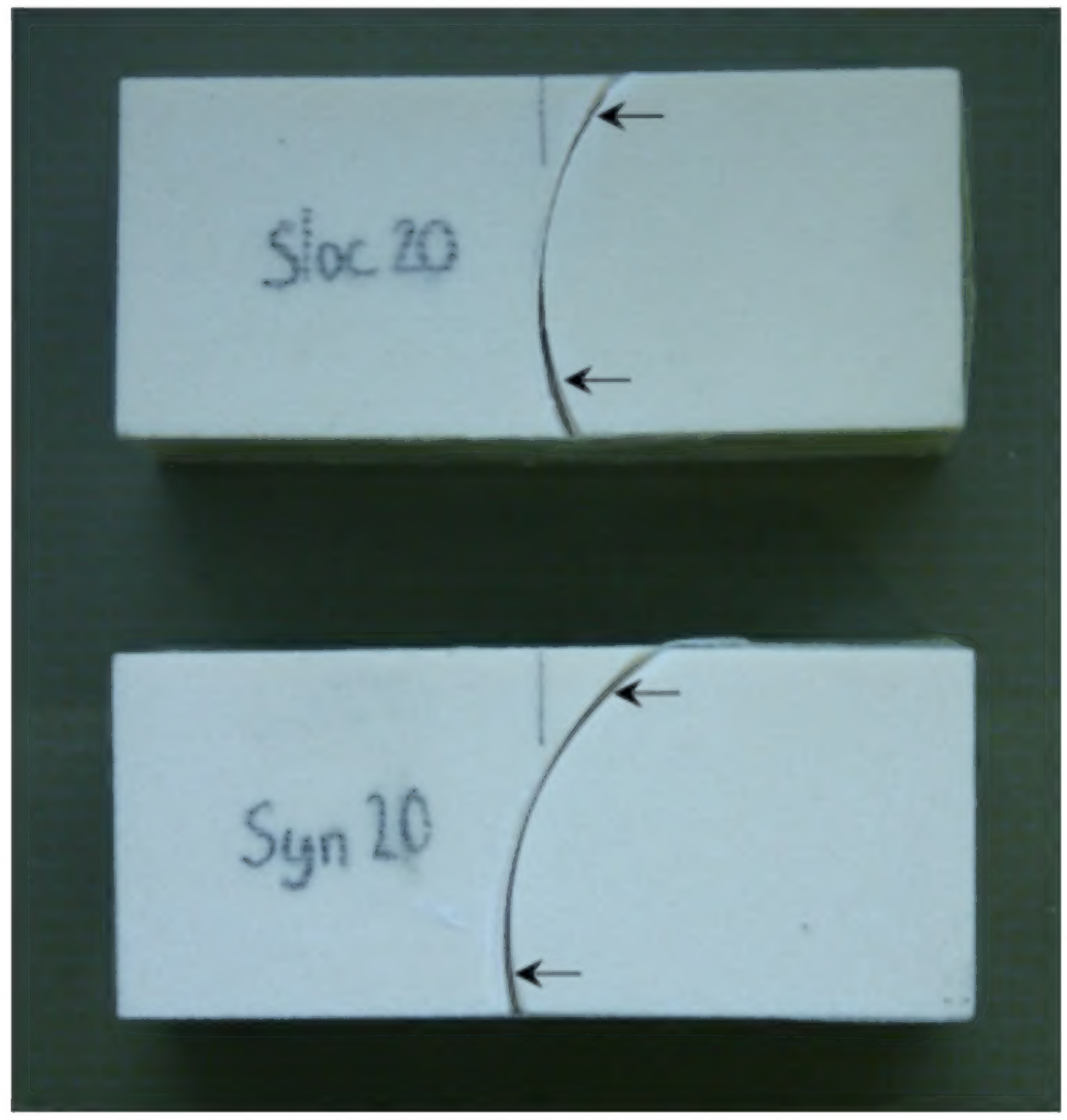

Figure 11 Test blocks from cutting trial 20 with the Slocum (top) and Synthes (bottom) oscillating saws. Compression was achieved using adhesive tape applied under tension around the circumference of the blocks. Arrows show peripheral gaps between the mated surfaces. No subjective difference was noted in the magnitude of this effect between the 2 blade designs.

with densities >2.5 times that of the chosen cancellous substitute yielded temperatures in excess of 200°C.

Although cadaveric bone remains an accepted test medium for orthopedic cutting experiments, it was not selected for this study because of 2 major limitations. Firstly, cadaveric bone of dogs without CrCL insufficiency is not representative of bone from CrCL-deficient dogs. A study examining proximal tibial metaphyseal bone density at 3 and 12 weeks after CrCL transection demonstrated density reductions of 170% and 190%, respectively.[18] Even in dogs treated immediately after CrCL transection by extracapsular stabilization (a scenario which more closely approximates chronic partial CrCL rupture), reductions in proximal tibial bone density of 18% were reported 10 weeks after surgery.[19] Fortunately, the extensive variety of commercially available Sawbone substitutes allowed us to closely match the proximal tibia of a CrCL-deficient dog in terms of test sample density.[23]

Table 3 Saw Blade Durability Expressed as Change in Tooth Height, Tip Width and Tooth Area

Tooth Dimension	Synthes	Slocum
Tooth height (new blade) (μm)	786	1155
Tooth height (20 uses) (μm)	531	1032
Reduction in tooth height (%)	32.4	10.6
Tip width (new blade) (μm)	8.75	43*
Tip width (20 uses) (μm)	195	118
Increase in tooth width (%)	2128	174
Tooth volume (new blade) (mm^3)	0.133	1.088
Tooth volume (20 uses) (mm^3)	0.12	1.046
Reduction in tooth volume (%)	9.77	3.86

*Tip width measured at the mid-point of the central tooth.

The 2nd major limitation of cadaveric canine tibia is the anatomic variability between test limbs. Despite the relatively uniform morphology of bovine diaphyseal femoral bone, previous authors have recorded marked variability in temperature curves between test samples.[9,22] While minimizing test sample variability is important for comparing dissimilar saw designs or analyzing the influence of irrigation, it becomes paramount during durability assessment, in which potential changes in performance are analyzed over multiple consecutive trials.[9] Another consideration of our model of *in vitro* performance testing is the thermal conductivity of the test samples. The thermal properties of bone tissue have not been well documented and the values reported differ widely.[24] Although the thermal conductivity of Sawbones is constant, it is about 50% lower than that of fresh human femora,[25] and this may have contributed to underestimation of bone temperatures in our study. It is noteworthy that several other factors, including a minimum distance restriction of the thermocouples from the cutting site, thermocouple size, thermal contact resistance, and thermocouple insertion position error, could also contribute to this potential error.[26] Despite this limitation, the temperature records previously reported *in vivo*

appear identical in shape and similar in magnitude to our *in vitro* measurements.[12] Moreover, it is unlikely that a significant improvement in this limitation could be achieved by use of dry cadaveric bone. Previous research has demonstrated decreases in thermal conductivity of as much as 4 times for dehydrated compared with fresh cadaveric bone.[24] Lastly, while cortical blood flow *in vivo* may dissipate some heat produced by sawing during operative procedures, it is unlikely that this cooling effect is significant.[24] Cortical flow rate is normally very low, and during sawing coagulation and occlusion of these small vascular channels probably occurs rapidly.[15]

Experimental Rig

The most appropriate orthogonal cutting model allows testing of saw blade performance with a constant, measured load applied to the blade.[8–11,14] Previous studies have demonstrated an inverse relationship between applied load and temperature elevation within the test specimen.[11,12,15] The distribution of heat is altered by increasing the force, with a greater proportion of heat in the cutting debris and less both in the instrument and the specimen.[26] In the clinical setting, surgeons do not transect bone at a uniform rate of advancement. Instead, they apply a relatively constant load to the blade that allows transection of the bone.[8] Krause et al[12] reported that cutting forces fluctuated between 4.5 and 7.5 N during a total hip revision performed using a reciprocating saw. Our choice of a 5 N force and 40 seconds sampling time was based on preliminary testing, in which a new Synthes blade at this thrust force resulted in cut durations of 35–40 seconds.

Most of the energy during orthogonal cutting is transformed into heat within the cutting debris.[27,28] This heat energy is subsequently dissipated in the debris, as well as in the test block and the tool by conduction.[27] The temperature gradient is very high at the tool–sample interface because the stainless steel blade has a much higher thermal conductivity and diffusivity than the sample being cut.[28,29] Consequently, the recorded sample temperature is dependent on the location of the thermocouple placement relative to the advancing saw as well as the length of time the test is run.[12] Previous studies measured temperature change during drilling tests using cadaveric samples of bovine mandible, and recorded reliable temperature curves when the thermocouples were positioned within 2 mm of the prospective position of the drill hole.[21] Other studies used thermocouples embedded in the cutting tools to measure the temperature at the tool-sample interface.[8–10,12,14,17,18] While this testing method is technically less demanding, it has several disadvantages compared with our methods. Firstly, as stated, the temperature within the cutting tool is not necessarily representative of the temperature within the test block itself. Additionally, the hole in which the thermocouple is placed represents a disturbance and may appreciably change the temperature field being measured.[29] Lastly, in those studies using thermocouples mounted on the oscillating saw blade, the thermocouple commonly became dislodged during cutting tests.[9,12]

Based on clinical experience, we anticipated some degree of skipping of the saw blade against the leading edge of the test block as a result of oscillating saw "chatter." The intended line of cut was positioned 1.5 mm from the thermocouples which allowed a tool–thermocouple distance within the recommended reference range, while minimizing the possibility of accidental trauma to the thermocouples by the advancing saw. Consequently, with the exception of 2 trials in which multiple thermocouple trauma occurred, and one trial in which trauma to the trans-cortex thermocouple was noted in isolation, the saw reliably bisected the line of cut throughout testing.

As expected, peak temperatures measured at each thermocouple were recorded when the cutting teeth were in close proximity. Previous studies have shown that cutting temperatures increase in proportion to the depth of cut,[12] and this effect could account for the higher temperatures measured at the mid-substance thermocouple. Explaining the lower temperatures measured at the trans-cortex is more challenging. Although it is tempting to speculate that the higher density of the cis- and trans-cortical polyurethane foam might indicate lower thermal conductivity compared with the mid-substance block, the thermal conductivity of the outer layers was actually 40% *higher* than that of the mid-substance cancellous block. Also, the same effect was seen in our pilot study when solid epoxy test blocks were used. Lastly, in clinical cutting experiments using blade-mounted thermocouples, the shape of the temperature curves followed the same trends, with maximum temperatures occurring in the mid-substance of the bone.[12] We are unaware of any hypotheses being forwarded to account for this effect.

Influence of Saw Design on Cutting Performance

During oscillatory cutting, a built up layer (BUL) forms on the rake face as well as the clearance face of the cutting tooth.[30] If the BUL is not cleared, debris tends to be pushed into the uncut work-piece in front of the teeth, resulting in a milling process instead of true cutting.[17,21] Clearance of the BUL is dependent on tooth geometry and mode of oscillation.[31] The mounting hub used by standard oscillating bone saws is oriented parallel to the saw blade, creating an arced cutting plane whose swing radius depends on the height of the blade.[8] During oscillatory cutting, the teeth are able to exit the work-piece, allowing the cutting debris at the interior teeth to be cleared from the cutting zone. An effect of the perpendicular alignment of the mounting hub relative to the saw teeth in TPLO blades is constant contact between the cutting teeth and the work-piece. Consequently, debris can only be cleared from the central teeth by the provision of tooth offset. This faculty results in the oscillating saw cutting a wider path than the thickness of the blade, allowing bone debris to move laterally, out of the way of the cutting zone.[8,31] Tooth offset is not a feature of the Slocum design, so the BUL can only be cleared from the peripheral teeth when they exit the work-piece because of overhang of the blade outside the sample.

This is considered a severe limitation of this design, especially as this last mechanism of debris clearance can be markedly obtunded in the clinical setting by the presence of the surrounding soft tissue envelope.[13]

Improvements in cutting tool performance are usually achieved either through the use of suitable tool geometries or by modifications to the tool material properties.[32] In depth discussion regarding the clinical ramifications of any small variations in alloy recipe between the 2 blades is considered inappropriate at the time of publication: No systematic study investigating the influence of steel grade on the tribological properties of martensitic steels has been published to date, and the influence of other important contributing factors such as microstructural variations and pretreatments (eg annealing and tempering) cannot be assessed. Also, no universally ideal cutting surface geometry exists, and the optimum geometry must be established for each particular set of cutting conditions.[33]

A fundamental parameter of orthogonal cutting with a key influence on cutting forces is the rake angle.[21,34] A positive rake angle, in which the tip of the tooth leads the base during cutting procedures, provides the optimal reduction in force and energy expenditure.[10,12,21,34] However, most tool manufacturers accept the provision of a negative rake angle allows a wider area of application because the teeth will cut during both the left and right motions of the oscillating blade. Krause and others showed that increases in negative rake angle resulted in decreased cutting efficiency.[21] They demonstrated a 2-fold increase in resultant cutting force when the rake angle increased negatively from 0° to −30°. Thus, in our controlled-force cutting experiment the −20° negative rake of the Synthes blade could, in part, account for its superior performance compared to the −25° Slocum blade.

Influence of Irrigation on Cutting Performance

While the lack of cooling effect with saline irrigation may appear counter-intuitive, it has been reported in 3 publications.[13,17,21] In 1991, two studies independently demonstrated that sawing procedures caused significant temperature elevations and that profuse irrigation with saline did not control the heat generation.[17,21] The authors explained the ineffectiveness of irrigation by hypothesizing that the coolant did not penetrate into the interior of the bone to allow debris to be cleared from the cutting zone. This hypothesis was tested when Toksvig-Larsen and others constructed a saw from 2 standard oscillating blades which were fixed to each other with channels between that allowed saline to emerge between the cutting teeth[13]; using this modified design they found that the temperature could be well controlled with a flow rate of 30–40 mL/min. When various single blade designs were compared with this double-blade configuration, saline irrigation was ineffective as a coolant. We are also aware of 2 previous studies that have demonstrated a positive impact of saline irrigation on the cutting performance of orthopedic saws. However, both studies are compromised by methodologies that do not appropriately model the clinical scenario: Ark and others effected a reduction in mean peak cutting temperature from 51°C to 23°C using high-speed pulsed saline irrigation, a technique which is not commonly used in clinical practice.[14] In another study, Krause and others reported reductions in mean peak cutting temperature from 171°C to 31°C using saline delivered by syringe.[12] However, in this study the tool being tested was a reciprocating saw, and the test block consisted of a small segment of mid-diaphyseal bovine femur rather than the complete circumference of the bone. Thus, access of the coolant to the cutting zone was considerably better than would be expected in the clinical setting.

In addition to the ineffectiveness of irrigation as a coolant, we also reported a significant reduction in cutting rate in the saline irrigated trials. As this finding contradicted the lubricating effect of saline proposed by the metal cutting industry,[32] we hypothesized that the high viscosity of the polyurethane debris in solution might have hindered rather than facilitated clearance of the BUL. We performed light microscopic analysis of the debris to confirm that the range of particle size was comparable to that of debris produced during TPLO of cadaveric canine bone (Fig 7). While it is acknowledged that the impact of the crystalline nature of the polyurethane debris on irrigant viscosity is unknown, a similar reduction in cutting rate has also been reported in a controlled force cutting experiment using cadaveric bone as the work-piece.[14] Thus, this hypothesis was conditionally rejected, as it appears that saline irrigation can hinder BUL clearance regardless of the physical characteristics of the debris.

Durability

Durability is an important measure describing the ability of a cutting tool to maintain its initial performance over multiple uses.[9] In practice, durability is directly related to wear, which involves the removal of tool material as a function of time in an abrasion environment.[35] The relationship between wear and durability has been well documented.[8,11,13,24,34] In 1987, Wevers and others examined a random sample of saw blades from an operating room and described their condition.[31] All 12 blades had some degree of damage to the cutting surfaces and major damage was observed in one-half of the blades. During performance tests using a dull saw blade, the force required to cut cortical bone was nearly 5-fold greater than that encountered with new blades.[13]

Wear rate depends on a combination of cutting forces, tool geometry, and material properties.[33] These variables are codependent; for example, a tool with suboptimal cutting surface geometry generates higher cutting forces, resulting in an increased rate of wear.[33] Edge retention or wear resistance is primarily determined by the materials hardness and the hardening method used.[36] The martensitic stainless-steel blades tested have improved hardness compared with precipitation-hardened stainless steel or austenitic stainless steel, and very similar alloy recipes to one another. However, although the macrohardness of the 2 blades should in theory be similar, microstructural differences and variable

pretreatments could influence wear rates in favor of the Slocum blade. Interestingly, one of the potential flaws of the Slocum design could also favor improved edge retention. Luo and others found that tooth geometries that limit removal of the BUL support formation of a coating on the tool face that prevents it from abrasion and thus wear.[37] The final variable affecting wear rate is hardness of the test block. Our test block substitutes were chosen to model proximal tibial cancellous bone in terms of density.[23] Fortunately, Young's modulus, bending strength, compressive strength, and tensile yield stress are all good predictors of material hardness,[36,38] and these properties were also well matched to the canine proximal tibia by our samples.[23] Thus, the wear behavior of the tools tested in our study should accurately represent their wear behavior in clinical practice. Our results showed that peak cutting temperature remained relatively constant over the course of 19 cuts, and, with the exception of the first trial using the Synthes saw, cutting rate did not show a declining trend with successive tests. Other authors have performed similar controlled force repeated cutting tests, and shown comparable durability profiles for new disposable blades tested over 80 trials.[9]

Our microscopic analysis involved imaging of the cutting surface in 2 planes, which necessitated removal of the distal 1 cm of the blade to allow mounting in the chamber of the SEM. As a result, we were only able to obtain images for wear analysis at 2 time points. We recorded a large drop-off in rate between cuts 1 and 3 for the Synthes blade, with the first trial having a cutting rate that was greater than 3 times faster than the third trial. Studies examining the wear behavior of stainless-steel knives have shown a significant drop in cut depth during the initial few cutting strokes because of a rapid rounding of the cutting edge.[39] A similar phenomenon may have occurred in our durability tests, but further study involving sequential SEM imaging would be required to test this hypothesis. Nonetheless, on the basis of our experience, and that of previous investigators,[21] we recommend that blades be regularly inspected after use using a $\times 10$ magnifying lens to identify signs of wear before they affect cutting performance. We have shown that 10–30% loss in tooth height appears tolerable, though further study is required to determine at what point tooth wear becomes clinically significant.

The magnitude of effect that the sharpening device exerted on the Slocum blade wear profile was not quantified. Although this could be interpreted as a study limitation, it is a direct consequence of performance testing according to the precise recommendations stipulated by the manufacturers. It is important to recognize that the superior durability of the Slocum blade (reported as improved resistance to wear) may be attributable to the use of a sharpening device.

Study Limitations

Limitations of our experimental model, including the lack of *in vivo* study, have been discussed and may prompt further study in this area. We tested a limited range of application of the TPLO blades, without investigating the performance of the complete range of blade size and design or the effects of intermittent cutting and irrigation. Current recommendations for tibial plateau osteotomy include creation of the osteotomy in at least 2 stages,[6] where the saw teeth could be cleaned and irrigated during the pauses in cutting. One study has shown that intermittent load was more effective in controlling temperature compared with a liquid coolant.[21] Thus, we feel that further study to assess the effects of intermittent loads and variable cutting rates on TPLO saw performance is warranted.

Our results favor the Synthes blade in terms of cutting performance and the Slocum blade in terms of wear resistance. However, our outcome measures do not take account of the principal proposed benefit of the Slocum blade, namely the biradial design feature.[7] While we did not intend to test Slocum's biradial hypothesis as part of our initial study protocol, we did perform trial reductions of the test blocks upon completion of the cutting tests. Subjectively, we could not detect any difference in the appearance of the reduced test blocks (Fig 11). We propose that this finding could have been anticipated: The biradial hypothesis assumes that the blade is driven straight across the bone without accounting for oscillation; however, when the blade oscillates the thicker more central portion is driven across the adjacent more peripheral thinner portion. Thus, depending on the magnitude of the oscillation arc, the biradial theory must be compromised.

Two other criteria used to support the use of either oscillating saw are instrument cost and ease of use. We are unable to comment on ease of use because our rig assembly effectively minimized saw "chatter," allowing a controlled line of cut with both saws. Also, cost considerations must account not only for the price of the blade itself, but for the cost of the oscillating saw, since the blade mountings are dissimilar for the Colibri and Slocum power tools.

Both saws produced temperatures exceeding the predetermined necrosis limit, and underestimation of the thermal response within bone represents the most likely error in our results. However, it is acknowledged that the necrosis limit is not a constant and depends on the duration for which bone experiences the elevated temperature.[15] The duration of our cutting trials, and consequently the interval above the predetermined necrosis threshold, was short. As a result, the degree of potential thermal damage to living tissue predicted by our results is unknown. However, based on cautious interpretation of our data, and previous experimental evidence, significant temperature elevation should be expected during TPLO. Limited efficacy of saline irrigation should also be assumed, and other precautions should be considered including maximizing feed rates and employing intermittent modes of cutting and coolant application.

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